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Invertebrates and vegetation of field margins adjacent to crops subject to contrasting herbicide regimes in the Farm Scale Evaluations of genetically modified herbicide-tolerant crops

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The effects of management of genetically modified herbicide-tolerant (GMHT) crops on adjacent field margins were assessed for 59 maize, 66 beet and 67 spring oilseed rape sites. Fields were split into halves, one being sown with a GMHT crop and the other with the equivalent conventional non-GMHT crop. Margin vegetation was recorded in three components of the field margins. Most differences were in the tilled area, with fewer smaller effects mirroring them in the verge and boundary. In spring oilseed rape fields, the cover, flowering and seeding of plants were 25%, 44% and 39% lower, respectively, in the GMHT uncropped tilled margins. Similarly, for beet, flowering and seeding were 34% and 39% lower, respectively, in the GMHT margins. For maize, the effect was reversed, with plant cover and flowering 28% and 67% greater, respectively, in the GMHT half. Effects on butterflies mirrored these vegetation effects, with 24% fewer butterflies in margins of GMHT spring oilseed rape. The likely cause is the lower nectar supply in GMHT tilled margins and crop edges. Few large treatment differences were found for bees, gastropods or other invertebrates. Scorching of vegetation by herbicide-spray drift was on average 1.6% on verges beside conventional crops and 3.7% beside GMHT crops, the difference being significant for all three crops.

Keywords: arable farming; Great Britain; butterflies; nectar resource; spray drift; vegetation

1. INTRODUCTION

Management of GMHT crops differs from that of conventional crops mainly in the type and timing of herbicides applied to the cropped area of fields (Champion *et al.* 2003). Field margins are, however, an important resource for plants and animals in the arable landscape (Marshall & Moonen 2002; Way & Greig-Smith 1987), and the effects of new management techniques on this component of agro-ecosystems need to be assessed.

Field margins can support a high diversity of plant species and are of conservation importance within farmed landscapes of Europe (Barr *et al.* 1993) and North America (Freemark *et al.* 2002). Field margins also provide a habitat for numerous invertebrates (Dover & Sparks 2000; Frank 1998; Morris & Webb 1987), a food resource for mammals (Tew *et al.* 1994), and a refuge for beneficial parasitoids (Powell 1986) and predators, e.g. carabid beetles (Bohan *et al.* 2000; Symondson *et al.* 1996). Margins provide resources for birds (Bradbury *et al.* 2000; Brickle *et al.* 2000; Lack 1992; Peach *et al.* 2001; Potts 1986) and bees (Fussell & Corbet 1992*b*; Svensson *et al.* 2000), and may be the only source of nectar and pollen in arable landscapes through much of the season.

The interactions between field margins and crops can have detrimental as well as positive agronomic impacts. Whereas margins provide overwintering sites for insects beneficial for pest control (Sotherton 1985), some slug species migrate into fields from the boundaries, causing significant crop damage around field edges (Frank 1998). The depredations of rabbits are notorious (Sheail 1972), and field-margin plants commonly harbour pests and pathogens (Norris & Kogan 2000).

Many declining farmland species are found within edges of fields. Conservation concern has focused on farmland birds (Brickle *et al.* 2000; Chamberlain *et al.* 2000; Donald & Vickery 2001; Evans *et al.* 1995; Potts 1986) but other species groups are also affected (Robinson & Sutherland 2002; Sotherton & Self 2000). The UK

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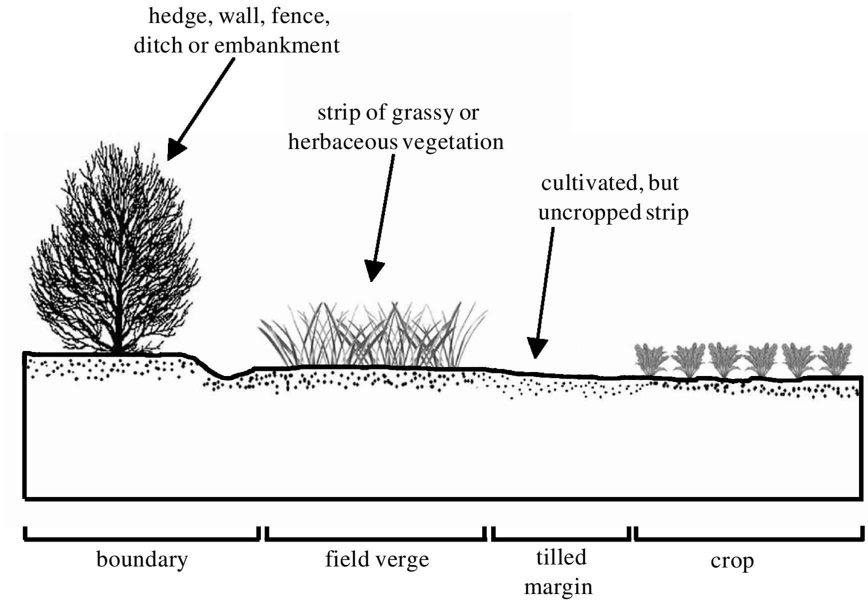

Figure 1. Cross-section of a field margin. Vegetation plots were sampled within the boundary, field verge and tilled margin.

Countryside Survey 2000 showed that, over a 20 year period, the vegetation of hedgerows had become on average less species-rich and more dominated by tall competitive plants associated with fertile conditions (Haines-Young *et al.* 2000). Over a longer period, many plants that have shown the greatest declines in distribution since the 1950s in Great Britain are those that are usually found in arable fields (Preston *et al.* 2002; Wilson 1992). The common butterflies of the farmed countryside have also suffered declines (Cowley *et al.* 1999). In arable environments this is mainly as a result of deterioration in both the quality and quantity of field margins (Asher *et al.* 2001). Bumblebees have reacted likewise, particularly in arable regions (Williams 1986).

Owing to their proximity to cropped land, field margins receive direct and indirect applications of pesticides. The effects of such spray drift are often small (Marrs & Frost 1997) but misplaced applications of herbicide can reduce plant cover and diversity (de Snoo 1997; de Snoo & van der Poll 1999), and may significantly reduce the abundances of ground beetles (Carabidae), spiders (Araneae), and true bugs (Heteroptera) (Haughton *et al.* 1999*a*,*b*) through lower sward height and an increased amount of dead vegetation (Haughton *et al.* 2001).

The aim of this paper is to compare the effects of management of GMHT and non-GMHT crops on key groups of flora and fauna in adjacent field margins; effects within the cropped area of the field are reported in accompanying papers on vegetation (Heard *et al.* 2003*a*,*b*) and invertebrates (Brooks *et al.* 2003; Haughton *et al.* 2003). For beet (*Beta vulgaris* ssp. *vulgaris* (L.)), maize (*Zea mays* (L.)) and spring oilseed rape (*Brassica napus* ssp. *oleifera* (DC.)) crops, we test a specific null hypothesis: that there is no difference between the management of GMHT varieties and that of comparable conventional varieties in their effects on the cover, flowering and seeding of vegetation, and the abundances of bees, butterflies, slugs and snails, and other invertebrates in the field margins. Where treatment effects are significant, we estimate their magnitude and consider the implications for farmland biodiversity of growing these GMHT crops. The main ecological effects of GMHT varieties are likely to be from the direct effects of herbicide regimes on vegetation, with knock-on indirect effects on associated invertebrate groups (Firbank *et al.* 2003*b*).

2. METHODS

The experimental design and statistical justification for the number of sites used in the trials have been outlined in detail elsewhere (Perry *et al.* 2003). The experiment ran from 2000 to 2002. Fields were selected from a pool on the basis of several criteria relating to biodiversity, management regimes and agricultural intensity to provide a sample of sites broadly representative of current British agriculture (Champion *et al.* 2003). In each field, the treatments (GMHT or conventional cropping) were allocated at random to each half.

The experiment contrasts the effects of crop-type management regimes (Firbank *et al.* 2003*b*; Squire *et al.* 2003). The main difference in crop management between treatments was in the herbicide regimes used. Differences in pesticide use, rotations, field-margin management or cultivation were allowed between half-fields if there were good agronomic reasons. In practice, management activities performed on field margins (such as mowing of verges, cutting of hedgerows and ditch clearance) are almost exclusively performed outside the cropping season.

(a) *The structure of field margins*

Various definitions and nomenclature are used to describe field margins. We follow the definitions of Marshall & Moonen (2002) who distinguished the crop edge (outer few metres of the crop), any margin strip present and the semi-natural habitat associated with the boundary. For the FSEs, cropped areas of fields were not treated as part of the field margin. Treatment effects in this part of the fields are reported in accompanying papers (Brooks *et al.* 2003; Haughton *et al.* 2003; Heard *et al.* 2003*a*,*b*). The three components of the field margin are defined as follows (figure 1). The tilled margin is the cultivated but uncropped strip at the edge of the field, a subset of the 'crop edge' as defined by Marshall & Moonen (2002). The field verge

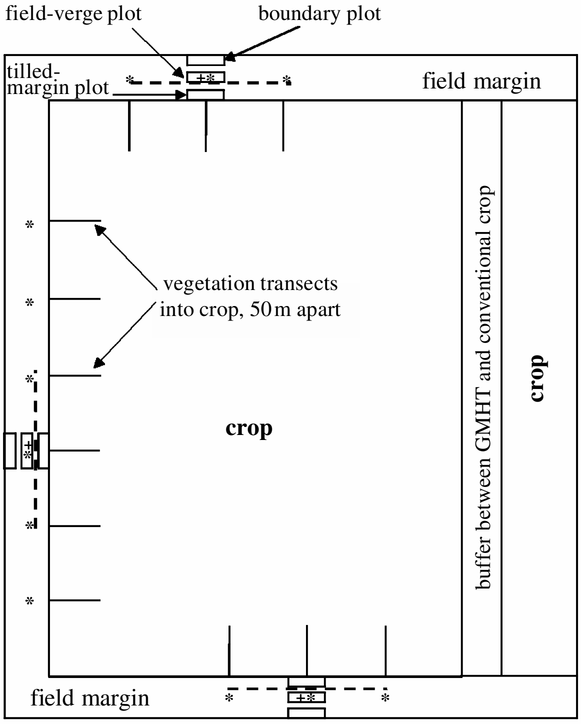

Figure 2. Location of margin sample points in a standard half-field. Symbols indicate sampling locations as follows: asterisk, gastropod searches and margin attribute samples; cross, suction samples; dashed line, bee and butterfly transects. Locations of vegetation plots are labelled.

is defined as the strip of grassy or herbaceous vegetation between the edge of the plough and the field boundary, termed a 'margin strip' by Marshall & Moonen (2002). The field boundary is taken to be any physical feature that is an interface between the field and another land-cover type, as defined by Marshall & Moonen (2002). A boundary is typically a hedge, wall, fence, ditch or embankment, but may be absent if two arable crops abut directly.

For those positions at which margin vegetation was recorded (figure 2) the widths of the tilled margin and verge were measured. At the ends of the 12 transects used for sampling vegetation in the crop, the presence or absence of a boundary hedge or ditch was noted within a 10 m length of margin (figure 2; Heard *et al.* 2003*a*).

(b) *Sampling vegetation*

The vegetation of the field margins was recorded by using plots located at the ends of three out of the 12 transects used for sampling vegetation in the crop (figure 2; Heard *et al.* 2003*a*). Each group of margin plots included a sample from within each of the three field-margin types defined above (boundary, field verge and tilled margin), provided that these features were present. The standard size of plot (10 m × 1 m) was chosen to coincide with that used in a national survey of the UK countryside (Haines-Young *et al.* 2000), but the plots were often in practice narrower, especially within the tilled margin. The full width of the tilled margin, verge or boundary was sampled when it was narrower than 1 m. Where no boundary existed (i.e. one crop was sown up against another) or where the verge was more than 30 m wide (e.g. game cover or set-aside), no boundary sample was taken.

Three types of vegetation record were made for each plot: vegetation cover was sampled in June; flowering and herbicide-spray damage were assessed in June, July and August (with an additional sample in May for beet); and records of seeding vegetation were taken in July and August. The timings were chosen to coincide with invertebrate sampling.

Estimates of the total cover of green plant material were made using the Braun-Blanquet scale (Lepš & Hadincová 1992; Mueller-Dombois & Ellenberg 1974). The cover, b_{ijkl}, of a species k (in plot l of treatment i at site j) was measured on a scale of 1–6 as follows:

$b_{ijkl} = 1$ if species present and cover is less than 1%;
$b_{ijkl} = 2$ if cover is 1–5%;
$b_{ijkl} = 3$ if cover is 5.1–25%;
$b_{ijkl} = 4$ if cover is 25.1–50%;
$b_{ijkl} = 5$ if cover is 50.1–75%; and
$b_{ijkl} = 6$ if cover is greater than 75%.

An overall estimate of cover was given for all grass species.

Flowering of species k was measured by two variables: f_{ijkl}, the frequency of flowering (the number of 1 m² subplots, out of 10, of the 10 m² plot l of treatment i at site j in which the species is found to be flowering) and the extent of flowering, e_{ijkl}, which was measured on a scale of 1–4 as follows, referring only to those subplots where species k was flowering:

$e_{ijkl} = 1$ if there were fewer than 10 individual blooms and less than 1% cover of blooms;
$e_{ijkl} = 2$ if there were not less than 10 individual blooms and less than 1% cover of blooms;
$e_{ijkl} = 3$ if blooms had 1–5% cover; and
$e_{ijkl} = 4$ if blooms had greater than 5% cover.

Flowers of grasses, sedges and rushes were not recorded to species.

Assessments of the damage from herbicide-spray drift refer only to that part of the plot that was (or was recently) vegetated. They do not include any bare ground in the plot. Thus 100% damage implies that all vegetation was browned (but there may be bare ground also). Likewise, 50% damage plus 50% bare ground implies that 50% of the ground is bare, 25% is vegetated and still green, and 25% is vegetated but browned by herbicide. Seed presence as ripe fruits on plants, including grasses, was recorded as a frequency out of 10 1 m² subplots.

(c) *Sampling bees and butterflies*

Bees and butterflies were counted by using the line-transect method developed for the UK BMS (Pollard & Yates 1993) and adapted as a standard method for bee surveys (Banaszak 1980). Transects were walked in June, July and August for all crops, with an additional sample in May for beet. Where possible, transects were walked beside maize and spring oilseed rape when the crop was in flower. The two halves of a split field were walked on the same day, the order being randomized because time of day affects flight activity. Walks were done between 10.00 and 17.30 when weather conformed to BMS standards (wind speed less than 5.5 m s^{-1}, not raining, temperature greater than 17 °C if sky overcast or greater than 13 °C if sky at least 60% clear). Three separate 100 m sections along the field margin were sampled, one on each side of the half-field in a standard field (figure 2). These sections were centred on the middle transect on each side of the half-field used to sample within-crop vegetation (figure 2; Heard *et al.* 2003*a*). Transect walks were done twice for each treatment with bees counted in one direction and butterflies counted in the opposite direction, the order being chosen at random. Bees were counted in field margins within 2 m of the crop edge and butterflies within 5 m. Transects were walked within the crop at the same time and are reported in Haughton *et al.* (2003).

Given the need to identify bees while on the wing, counts were made for groups of bumble-bee (*Bombus*) species based on colour type (according to Prys-Jones & Corbet (1991)). Each colour group contains one or two species that are common in southern Britain and one or two rare and localized species, which are difficult to separate without capturing the insects. The common species in each colour group are shown in brackets: black and red tail (*B. lapidarius*); brown/ginger (*B. pascuorum*); one or two yellow bands with red tail (*B. pratorum*); two yellow bands with white or buff tail (*B. terrestris*/*B. lucorum*); three yellow bands with white tail (*B. hortorum*). Separate counts were made for honeybees, cuckoo bees (*Psithyrus*) and solitary bees. In all cases, only actively foraging individuals or nest-searching queens were counted. The flowering species on which the bees were foraging were listed. Counts were made separately for all butterfly species.

(d) *Sampling slugs and snails*

Slugs and snails (gastropods) were counted in 12 areas around the field, located at the ends of the transects used for sampling vegetation in the crop (figure 2; Heard *et al.* 2003*a*). Where the verge was up to 1 m wide, each sampling area consisted of a 2 m length of the verge over its full width. Where this feature was over 1 m wide, a 2 m × 1 m sampling area was used. Within each sampling area, a visual search was made for 4 min. The vegetation within the plot was gently parted, by hand, to reveal any slugs and snails present. Those found during the 4 min search were retained for identification at the end of the search. All gastropods collected were identified *in situ*, where possible; however, some were removed to the laboratory for later identification. The searches took place after, but within one week of, the vegetation sampling. The timing of sampling was adjusted, where possible, so that the forecast daily air temperature was in the region 10–18 °C, the weather was overcast and the soil surface and vegetation were visibly moist.

(e) *Sampling other invertebrates by using a suction sampler*

Invertebrates were sampled by using a Vortis suction sampler (Arnold 1994). The Vortis sampler has an aperture diameter of 15.5 cm and is comparable to the bulkier D-vac suction sampler. Such devices have been used widely in similar entomological field studies (e.g. Haughton *et al.* 2001; Maudsley *et al.* 1997; Moreby *et al.* 1997) and were used for invertebrate assessments within the crop (Haughton *et al.* 2003). Although extraction efficiency is always less than 100%, suction samples represent a consistent proportion of the population present and thus allow direct statistical comparisons of abundance between treatments for the same habitat.

Samples comprised five 10 s sub-samples taken 1 m apart in the verge. These were taken at three locations around each half of the field in June and August. Samples were taken from dry vegetation, and sampling positions and timings coincided as closely as possible with those for vegetation sampling (figure 2). The area of verge sampled in each half-field per year was approximately 0.56 m^2.

Invertebrate samples were placed in labelled polythene bags in a cool box containing frozen blocks during transit from the field, and then stored in a freezer in the laboratory. The invertebrates were separated from other organic matter and soil particles by repeated flotation before being counted and identified to the taxonomic level specified for each major group (table 1).

(f) *Analysis*

(i) *Response variables*

All analyses were based on totals per half-field. Indices of plant-species density, flowering and seeding were calculated for the three components of the field margin (tilled margin, field verge and boundary). Indices of flowering and seeding were also calculated for separate months.

The index of plant cover, C_{ij}, was calculated as the sum of the cover scores of the n_s species recorded per half-field as:

$$C_{ij} = \sum_{k=1}^{n_s} \sum_{l=1}^{3} b_{ijkl},$$

where b_{ijkl} is the cover score (1–6) of species k in plot l for treatment i at site j.

An index of flowering of vegetation, F_{ij}, was calculated as the sum of the products of the frequency and extent of the flowering of the n_s species recorded per half-field as,

$$F_{ij} = \sum_{k=1}^{n_s} \sum_{l=1}^{3} f_{ijkl} \times e_{ijkl},$$

where f_{ijkl} is the frequency of flowering (in 10 1 m^2 subplots of the 10 m^2 plot) and e_{ijkl} (out of four) is the extent of flowering of species k in plot l for treatment i at site j. A flowering index was calculated separately for each of the plant families (Asteraceae, Brassicaceae, Fabaceae, Lamiaceae, Rosaceae, Scrophulariaceae) that have previously been identified as being important nectar sources for bees and/or butterflies (Feber *et al.* 1996; Fussell & Corbet 1992*a*; Meek *et al.* 2002).

A seeding index was calculated as the frequency of species recorded seeding within the same plots:

$$S_{ij} = \sum_{k=1}^{n_s} \sum_{l=1}^{3} s_{ijkl},$$

where s_{ijkl} is the frequency of seeding (in 10 1 m^2 subplots of the 10 m^2 plot) of species k in plot l for treatment i at site j.

Bee and butterfly counts were analysed as totals summed over individual months and for the whole season. The responses of honeybees (*Apis mellifera*), bumble-bees (*Bombus* spp. and *Psithyrus* spp.) and a subgroup of long-tongued bumble-bees (*B. hortorum*, *B. pascuorum* and bees in the same colour groups) were also analysed separately. Long-tongued bumble-bees were chosen because they are selective about the plants they feed on and may be particularly sensitive to any reduction in floral resources in farmland. The responses of *Pieris* and non-*Pieris* butterflies were analysed separately for spring oilseed rape, as cultivated brassicas such as this are foodplants of small white (*P. rapae*) and large white (*P. brassicae*) butterflies. Totals from spring and autumn slugs-and-snails samples were analysed separately as well as combined season totals. Totals of invertebrates sampled by suction sampling were also analysed as counts from separate sampling occasions in addition to totals over the whole season. The following taxonomic groups were analysed: ground beetles (Carabidae: family and selected species), true bugs (Heteroptera: suborder, herbivores and predators), spiders

Table 1. Levels of identification and assigned major functional groups of suction-sampled invertebrates in the field margins. (Collembola are not assigned to a functional group; invertebrates identified as important food resources for birds follow Wilson *et al.* (1999); y, present in assigned functional group.)

		functional group			
taxa	level of identification	predator	herbivore	parasitoid	bird food
Collembola	family	—	—	—	—
Orthoptera	order	—	—	—	y
Hemiptera					
Heteroptera	species	y	y	—	y
Auchenorrhyncha	species	—	y	—	y
Aphidoidea	superfamily	—	y	—	y
Neuroptera	order	y	—	—	—
Lepidoptera					
larvae	order	—	y	—	y
Diptera	order	—	—	—	y
Hymenoptera					
Symphyta larvae	suborder	—	y	—	y
Parasitica	superfamily	—	—	y	—
Coleoptera					
Coccinellidae	species	y	y	—	—
Curculionidae	family	—	y	—	y
Staphylinidae	family	y	—	—	y
Carabidae	species	y	—	—	y
others	order	—	—	—	—
Araneae					
Linyphiidae	family	y	—	—	y
Lepthyphantes tenuis	species	y	—	—	y
Erigone	genus	y	—	—	y
Oedothorax	genus	y	—	—	y
Lycosidae	family	y	—	—	y
others	order	y	—	—	y

(Araneae: order and selected species) and springtails (Collembola: order and families). Invertebrates sampled by suction sampling were assigned to functional groups based on their role in the movement of resource from primary production to decomposition (herbivores, predators, parasitoids) (Lindeman 1942; Hawes *et al.* 2003). Numbers of these functional groups were analysed, as was a group of invertebrates identified as an important food resource for birds (table 1; Wilson *et al.* 1999).

(ii) *Statistical analysis*

A description of the experimental design has been given in detail elsewhere (Perry *et al.* 2003) and is only summarized briefly here. Records for each variate analysed were obtained from systematic samples within half-fields of three spring crops, in a randomized block experimental design, in which the blocks were paired half-fields. The total count, c_{ij}, per half-field, for treatment i at site j, was transformed to $l_{ij} = \log(c_{ij} + 1)$. To give an approximate indication of abundance, geometric means for each treatment i were calculated from back-transformed arithmetic means of l_{ij}. The standard analysis of abundance was a randomized block analysis of variation of the transformed values, l_{ij}, termed the lognormal model by Perry *et al.* (2003). The null hypothesis was tested with a paired randomization test, using as a test statistic $d = \Sigma_j[l_{2j} - l_{1j}]/n$ for n sites, the mean of the differences between the GMHT and conventional treatments on a logarithmic scale. The treatment effect was measured as R, the multiplicative ratio of the GMHT treatment divided by the conventional treatment, calculated as $R = 10^d$; confidence intervals about R were obtained by back-transformation of the confidence interval of d on the logarithmic scale, derived from the standard error of d and $t_{0.05}$. Response variables were analysed separately for each occasion and for all occasions totalled over the season. Where differences in treatment effects between occasions were minimal, results are given for all occasions totalled over the entire season. Sites, j, for which the whole-field total count, $c_{1j} + c_{2j}$, was zero or unity were removed from the analyses. For analyses of margin attributes and vegetation scorching, all sites were analysed and differences in arithmetic means were assessed using a paired t-test.

Where large treatment effects were found ($p < 0.05$), separate covariate analyses were done to test for consistency of treatment effects between years, in relation to the weed status of sites, between environmental regions and between sugar beet and fodder beet. The potential density of weeds from an initial sample of the seedbank (Heard *et al.* 2003*a*) was taken as a measure of the overall potential weed status of each site. The six environmental zones (Firbank *et al.* 2003*a*; Haines-Young *et al.* 2000) of the Institute of Terrestrial Ecology Land Classification of Great Britain (Bunce *et al.* 1996) were used to group sites with similar topography and climate.

3. RESULTS

(a) *Characteristics of the field margin*

No differences were found in the frequencies of hedgerow or ditch on margins adjacent to any of the three crops (table 2). The average widths of tilled margins were 1.2 m, 0.8 m and 0.7 m for beet, maize and spring oilseed rape, respectively, and did not differ between treatments. Verges were on average 0.9 m, 1.1 m and 1.2 m wide for beet, maize and spring oilseed rape, respectively, and again did not differ between treatments (table 2).

(b) *Treatment effects on vegetation*

Common nettle (*Urtica dioica*), common couch (*Elytrigia repens*), creeping thistle (*Cirsium arvense*) and cleavers (*Galium aparine*) were frequent within the tilled margin, field verge and boundary occurring in over 70% of plots sampled for each type. The plant composition of the tilled margin was similar to that found in the cropped area of the field. The twelve most frequent and abundant weed species found within the crop (Heard *et al.* 2003*b*) also occurred within tilled margins of more than 60% of plots sampled.

(i) *Cover*

For spring oilseed rape, the indices of plant cover in the tilled margin, field verge and boundary of the GMHT half-fields were 25%, 19% and 25% lower, respectively, than on the conventional half-fields (table 3*a*). In maize, the index of cover was greater in GMHT halves by 28% and 15% in tilled-margin and field-verge samples, respectively, but no differences were found in boundary plots. There was no treatment difference in plant cover for any of the field-edge plots sampled adjacent to beet.

(ii) *Flowering*

The plants recorded flowering in field margins were similar for all three crops. Species flowering in more than 20% of tilled-margin plots were common field-speedwell (*Veronica persica*), shepherd's-purse (*Capsella bursa-pastoris*), field pansy (*Viola arvensis*) and groundsel (*Senecio vulgaris*). Within verge plots, common nettle, cleavers, hogweed (*Heracleum sphondylium*) and creeping thistle were most frequently flowering, and bramble (*Rubus fruticosus*), common nettle and cleavers flowered in more than 20% of boundary plots.

Over the whole season, the flowering resource available within tilled margins was greatest adjacent to spring oilseed rape crops, but of similar magnitude beside beet crops (table 3*b*). The average whole-field geometric mean counts for beet and spring oilseed rape were 72.3 and 83.6, respectively. The flowering index was less than half this amount on average in tilled margins of maize. For this crop, flowering was greatest within field-verge samples.

For all three crops studied, treatment differences in flowering were found within the tilled margins of fields. Flowering adjacent to beet and spring oilseed rape was lower for GMHT half-fields, but greater adjacent to maize.

The most consistent effects were found for the tilled margins of spring oilseed rape, with less flowering throughout the season. The greatest difference was found in July, with a flowering index 53% lower in GMHT tilled margins (table 3*b* and figure 3). The flowering index was also lower in June verge samples of the GMHT halves of the same crop, by 34% (table 3*b*), but not for other months sampled. Flowering of plant families that are important nectar sources for bees and butterflies was also lower throughout the season in tilled margins of spring oilseed rape (table 4). No differences in flowering were found in boundaries of spring oilseed rape.

Over the whole season, tilled margins of GMHT halves of beet fields had 34% less flowering than conventional half-fields (table 3*b*). Differences were greatest in July, 54% lower on GMHT halves, and comparable to those found in spring oilseed rape tilled margins at the same time of the year (table 3*b* and figure 3). The flowering index of Asteraceae was similarly reduced in GMHT tilled margins in July (table 4). Flowering differences were also found in August for Asteraceae and Brassicaceae but in opposite directions: a greater flowering index was found in GMHT tilled margins for Brassicaceae but a lower index for Asteraceae. No differences were found in flowering in field-verge or boundary samples for this crop.

Flowering in tilled margins of maize crops was greater in GMHT half-fields, by 98% in August and 67% over the whole season (table 3*b*). The flowering indices of Brassicaceae, Fabaceae and Scrophulariaceae were also greater in GMHT tilled margins in August and when totalled over the season (table 4). Differences were also found in boundary samples for this crop, with 118% more flowering in GMHT half-fields in August and 32% more over the whole season (table 3*b*).

(iii) *Seed set*

The frequency of seeding species was three to four times higher in field verges than in tilled margins and field boundaries (table 3*c*). There was a large treatment effect on seeding within tilled margins of beet and spring oilseed rape fields, with 39% and 35% less seed, respectively, over the whole season in GMHT than in conventional half-fields. August seeding was also lower in GMHT tilled margins for these crops, by 37% for beet and 32% for spring oilseed rape. Fewer seeding species in field verges adjacent to GMHT beet crops were found in August (table 3*c*), despite no effects on flowering or plant-species density being found in this component of field margins for this crop (table 3*a*,*b*). No differences in seeding were found in field-margin samples adjacent to maize crops.

(iv) *Spray damage*

Differences in the amount of scorched vegetation were found in the tilled margins of all three crops (table 5). Effects were most marked in beet, with a higher percentage of vegetation scorched from June onwards, with 4.4% more overall and reaching a maximum in July of 6.7% more. The amount of bare ground was also different between treatments within tilled margins of beet fields, with 22% for GMHT halves compared with 17% for conventional halves on average. Less overall scorching was found in the field verge and boundary for beet, with 2.6% and 0.5%, respectively, but again considerably more was found in GMHT halves (table 5).

A higher proportion of vegetation was also scorched in GMHT field margins adjacent to maize and spring oilseed rape. Differences were greater in tilled margins than within the verge, with 3.1% compared with 1.5% more scorching in maize and 2.5% versus 2% in spring oilseed rape. Within the season, effects were found in June and July for maize, but only in June for spring oilseed rape (table 5).

Table 2. Attributes of field margins.
(Hedge and ditch frequencies (out of 12) are given as mean values; widths of tilled margin and field verge are median values in metres. Arithmetic means for conventional (C) and GMHT treatments are values per 10 m^2 for n sites included in the analysis. CI, confidence interval.)

		arithmetic mean count			
crop and margin characteristic	n	C	GMHT	difference between treatments (95% CI)	p-value
beet					
tilled-margin width	66	0.98	1.37	1.22 (−0.31–2.76)	0.12
field-verge width	66	0.93	0.95	0.45 (−0.35–1.25)	0.26
hedge frequency	66	4.50	4.86	0.36 (−0.53–1.25)	0.42
ditch frequency	66	2.33	2.03	−0.30 (−0.93–0.33)	0.34
maize					
tilled-margin width	59	0.85	0.84	0.03 (−0.07–0.12)	0.59
field-verge width	59	1.08	1.21	0.39 (−0.57–1.35)	0.42
hedge frequency	59	5.66	5.34	−0.32 (−1.26–0.61)	0.49
ditch frequency	59	2.05	1.81	−0.24 (−0.94–0.47)	0.50
spring oilseed rape					
tilled-margin width	67	0.63	0.68	0.84 (−0.49–2.16)	0.21
field-verge width	67	1.29	1.04	−0.32 (−2.38–1.73)	0.75
hedge frequency	67	5.72	5.24	−0.48 (−1.34–0.39)	0.27
ditch frequency	67	2.54	3.21	0.67 (−0.17–1.51)	0.11

(c) *Bees and butterflies*

For all three crops sampled, small white (*P. rapae*) was the most abundant butterfly species recorded, making up over half of all individuals seen on the edges of spring oilseed rape crops and approximately a quarter of those seen on the margins of beet and maize crops. Large white (*P. brassicae*), meadow brown (*Maniola jurtina*), small tortoiseshell (*Aglais urticae*) and green-veined white (*P. napi*) were also commonly found, together comprising 45%, 44% and 34% of individuals recorded on beet, maize and spring oilseed rape tilled margins, respectively. The most consistent treatment effects on butterfly numbers were found for spring oilseed rape crops (table 6 and figure 3*b*). For *Pieris*, non-*Pieris* and the two combined over the whole season, counts were lower on margins of GMHT half-fields. Differences were greater for non-*Pieris* than *Pieris* species: 37% compared with 19% lower densities, respectively, on GMHT margins relative to conventional ones. Within the season, counts were lower on GMHT margins by the greatest amount in July for *Pieris*, 39%, but in August for non-*Pieris*, 40%. Counts for all eight individual species analysed were also consistently lower on spring oilseed rape GMHT margins. Over the whole season, the total numbers of butterflies on margins were not different for beet. However, butterfly numbers recorded in July from this crop were lower in margins adjacent to GMHT half-fields by 27% (table 6 and figure 3). Numbers of small tortoiseshells over the whole season were also lower in GMHT beet than in conventional beet. No differences in butterfly densities were found on margins around maize crops (table 6).

The bumble-bee (*Bombus*) species *B. terrestris*, *B. lucorum*, *B. lapidarius* and *B. pascuorum* and the honeybee *Apis mellifera* were the most frequently recorded bees in all crops. They were recorded visiting 66 different plant genera from 30 families. In the margins of all three crops, they were most often recorded on thistles (*Cirsium* spp.), hogweed (*H. sphondylium*) and bramble (*R. fructicosus*). For all three crops, counts were low and variable and no differences were found in total density of all bees between margins of GMHT and conventional half-fields (table 7). However, differences were found between groups of bees in margins of beet crops in June. Counts of bumble-bee and long-tongued bee groups were greater by 74% and 71%, respectively, in GMHT margins at this time of the year, but lower by 52% for honeybees; no difference was found in total bee numbers. Honeybee density was greater by 182% in August in GMHT margins of maize, but no other differences in bee numbers were found for this crop. Bee counts were highest in July, and the density of bees was much greater on margins next to spring oilseed rape than on those adjacent to beet and maize crops, but no treatment differences in bee densities were found on these margins.

(d) *Other invertebrates*

(i) *Slugs and snails*

Three main gastropod species found in field verges of all three crops were the snails *Monacha cantiana* and *Cepaea hortensis*, and the slug *Deroceras reticulatum*. No treatment effects were found for gastropods within any of the three crops sampled (table 8).

(ii) *Ground beetles (Carabidae)*

The most abundant ground beetles were *Bembidion lampros*, *Trechus quadristriatus* and *Demetrias atricapillus*, which represented 12%, 14% and 5% in beet; 19%, 6% and 8% in maize; and 16%, 7% and 12% in spring oilseed rape field verges, respectively. Of the species analysed, although counts were low, the abundance of *B. lampros* was shown to be 105% higher, whereas that of *D. atricapillus* was 44% lower, in field verges of GMHT maize (table 9*a*). No other species showed treatment effects.

Table 3. Margin vegetation in relation to treatments in each half-field for (*a*) index of plant cover, (*b*) index of flowering and (*c*) index of seeding.
(Geometric means for conventional (C) and GMHT treatments are values per 10 m^2 for n sites included in the analysis. Multiplicative treatment ratio, $R = 10^d$, where d is the mean of the differences between GMHT and C treatments on the logarithmic scale; confidence limits for R are back-transformed from those for d. CI, confidence interval.)

		geometric mean			
(*a*) crop and margin location	n	C	GMHT	R (95% CI)	p-value
beet					
tilled margin	62	7.49	7.71	1.03 (0.79–1.33)	0.84
field verge	61	10.6	11.1	1.04 (0.79–1.38)	0.77
boundary	62	6.68	6.49	0.97 (0.67–1.41)	0.88
maize					
tilled margin	48	7.54	9.73	1.28 (1.06–1.54)	0.006**
field verge	49	14.2	16.3	1.15 (1.03–1.27)	0.012*
boundary	48	10.0	11.8	1.17 (0.89–1.55)	0.27
spring oilseed rape					
tilled margin	64	9.31	6.85	0.75 (0.62–0.90)	< 0.001***
field verge	64	13.7	11.1	0.81 (0.70–0.94)	0.004**
boundary	65	9.60	7.14	0.75 (0.59–0.96)	0.016*

			geometric mean			
(*b*) crop and margin location	period	n	C	GMHT	R (95% CI)	p-value
beet						
tilled margin	year	66	87.3	57.2	0.66 (0.50–0.86)	< 0.001***
	May	23	2.31	2.63	1.12 (0.52–2.41)	0.76
	June	42	4.70	6.85	1.43 (0.83–2.44)	0.19
	July	62	29.8	13.5	0.46 (0.32–0.66)	< 0.001***
	August	64	47.3	29.3	0.62 (0.46–0.85)	0.002**
field verge	year	66	65.7	61.5	0.94 (0.66–1.32)	0.71
	May	36	19.1	14.5	0.76 (0.49–1.19)	0.22
	June	50	26.1	23.5	0.90 (0.58–1.41)	0.66
	July	63	25.0	19.8	0.79 (0.53–1.18)	0.25
	August	62	17.9	16.5	0.92 (0.65–1.32)	0.67
boundary	year	66	20.1	21.0	1.04 (0.66–1.65)	0.87
	May	33	7.11	9.39	1.31 (0.65–2.64)	0.44
	June	48	10.8	10.7	1.00 (0.59–1.69)	0.99
	July	58	9.09	6.75	0.75 (0.46–1.23)	0.25
	August	55	5.41	8.12	1.47 (0.89–2.44)	0.14
maize						
tilled margin	year	58	25.7	43.1	1.67 (1.16–2.40)	0.009**
	June	33	2.38	3.09	1.26 (0.65–2.47)	0.47
	July	50	8.04	10.4	1.28 (0.72–2.30)	0.38
	August	55	15.3	30.5	1.98 (1.32–2.97)	< 0.001***
field verge	year	58	87.0	94.9	1.09 (0.95–1.25)	0.20
	June	48	31.4	29.4	0.94 (0.71–1.23)	0.63
	July	54	28.2	30.4	1.07 (0.89–1.30)	0.44
	August	55	23.0	30.0	1.30 (1.00–1.69)	0.056
boundary	year	57	35.8	47.2	1.32 (1.03–1.68)	0.018*
	June	47	17.0	18.9	1.11 (0.73–1.69)	0.64
	July	52	11.1	12.2	1.09 (0.77–1.55)	0.64
	August	52	4.15	9.41	2.18 (1.36–3.49)	0.002**
spring oilseed rape						
tilled margin	year	67	101	66.1	0.66 (0.54–0.80)	< 0.001***
	June	48	8.87	4.84	0.56 (0.35–0.91)	0.019*
	July	64	39.7	18.4	0.47 (0.33–0.66)	< 0.001***
	August	66	42.5	31.2	0.74 (0.57–0.95)	0.027*
field verge	year	67	105	87.6	0.83 (0.68–1.02)	0.083
	June	57	34.0	22.2	0.66 (0.49–0.88)	0.005**
	July	64	33.3	30.5	0.92 (0.67–1.26)	0.59
	August	66	27.3	25.7	0.94 (0.72–1.23)	0.66

(*Continued.*)

Table 3. (*Continued.*)

(*b*) crop and margin location	period	*n*	geometric mean C	GMHT	*R* (95% CI)	*p*-value
boundary	year	67	41.7	36.6	0.88 (0.64–1.20)	0.43
	June	57	16.8	12.0	0.72 (0.46–1.12)	0.15
	July	64	10.8	9.44	0.88 (0.55–1.41)	0.60
	August	64	6.90	6.90	1.00 (0.63–1.58)	1.00

(*c*) crop and margin location	period	*n*	geometric mean C	GMHT	*R* (95% CI)	*p*-value
beet						
tilled margin	year	62	4.19	2.41	0.61 (0.43–0.86)	0.007**
	July	36	2.04	1.29	0.68 (0.42–1.12)	0.13
	August	58	3.15	1.86	0.63 (0.43–0.91)	0.015*
field verge	year	65	16.0	12.0	0.76 (0.57–1.01)	0.062
	July	61	6.91	5.41	0.79 (0.59–1.07)	0.13
	August	62	9.46	6.13	0.66 (0.48–0.91)	0.004**
boundary	year	61	3.94	4.03	1.02 (0.69–1.52)	0.92
	July	44	2.48	1.85	0.77 (0.47–1.26)	0.29
	August	56	2.73	2.82	1.03 (0.67–1.58)	0.88
maize						
tilled margin	year	43	2.58	3.72	1.40 (0.87–2.23)	0.15
	July	27	1.49	1.29	0.89 (0.52–1.54)	0.68
	August	40	2.06	3.07	1.42 (0.86–2.33)	0.16
field verge	year	56	21.0	23.6	1.12 (0.94–1.34)	0.21
	July	51	8.78	9.40	1.07 (0.85–1.34)	0.56
	August	54	13.4	14.3	1.06 (0.88–1.28)	0.52
boundary	year	54	4.28	5.76	1.32 (0.93–1.88)	0.12
	July	41	2.12	2.09	0.99 (0.66–1.48)	0.97
	August	46	3.33	5.06	1.47 (0.98–2.22)	0.057
spring oilseed rape						
tilled margin	year	64	6.26	3.97	0.65 (0.51–0.84)	0.002**
	July	41	2.19	1.47	0.71 (0.46–1.11)	0.13
	August	63	4.56	2.98	0.68 (0.52–0.88)	0.005**
field verge	year	67	18.3	20.0	1.09 (0.92–1.31)	0.35
	July	60	6.20	6.63	1.07 (0.83–1.37)	0.64
	August	66	11.5	12.1	1.05 (0.86–1.27)	0.70
boundary	year	61	6.77	5.74	0.86 (0.63–1.16)	0.30
	July	40	3.43	2.58	0.77 (0.50–1.21)	0.25
	August	59	4.66	4.52	0.97 (0.69–1.37)	0.87

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

(iii) *True bugs (Heteroptera)*

There were no treatment effects on total numbers of true bugs in any of the three crops. Samples were dominated by nymphs, which restricted species-level identification. The abundance of herbivorous true bugs was 50% lower in June, but not in August, in the field verge adjacent to GMHT beet (table 9*a*). No differences in abundance were found on field verges beside maize or spring oilseed rape.

(iv) *Springtails (Collembola)*

More than 98% of the springtails belonged to the Entomobryidae, Isotomidae or Sminthuridae, which represented 58%, 35% and 6% in beet; 53%, 33% and 12% in maize; and 56%, 28% and 15% in spring oilseed rape field verges, respectively. In August samples, total springtail numbers in the field verge were 37% greater in GMHT maize than in conventional maize, and Sminthuridae abundance was 69% greater in the field verge beside GMHT spring oilseed rape (table 9*a*).

(v) *Spiders (Araneae)*

Treatment effects on total spider numbers were detected only in maize, where there were 16% fewer in the GMHT treatment. Sheet web spiders (Linyphiidae) represented 26%, 30% and 37% of total adult spiders in beet, maize and spring oilseed rape field verges, respectively, and the abundance of this group of spiders was 29% lower in GMHT maize than in conventional maize over the whole season and 33% lower in GMHT spring oilseed rape in June.

(vi) *Functional groups*

Treatment differences for herbivores and parasitoids were found in August samples from field verges beside beet, where abundance was 28% lower in the GMHT

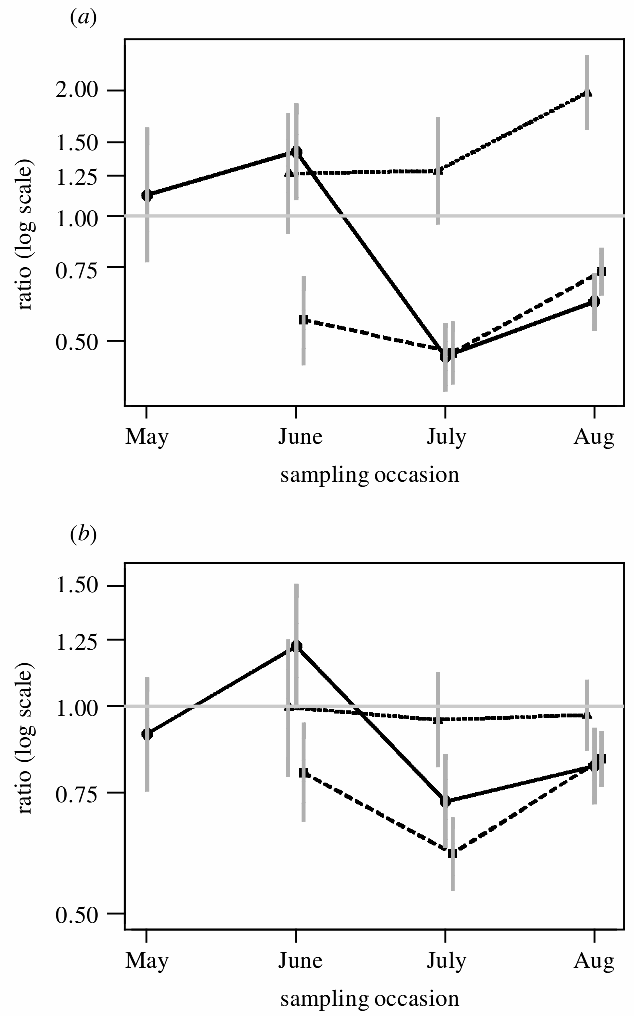

Figure 3. Main effects of treatment on (*a*) flowering in tilled margins and (*b*) butterflies expressed as a ratio (GMHT : conventional) for each month. Symbols (line style) for different crops: filled circle (solid line), beet; triangle (dotted line), maize; square (dashed line), spring oilseed rape. Error bars are one standard error.

treatment for both groups (table 9*b*). There were no treatment effects on predators or invertebrate bird-food items in any of the three crops (table 9*b*).

(e) *Consistency of treatment effects: treatment × covariate interactions*

Excluding analyses of vegetation scorching and margin attributes, out of the 72 significant treatment effects found (tables 3, 4 and 6–9) seven showed a significant treatment × year interaction. In all but one of these cases, the magnitude, but not the direction, of the effect differed in one of the three years analysed. There was no consistent pattern in the year that differed. For one effect, cover index of vegetation in tilled margins of maize, the effect was apparent only in the third year, and the treatment differences were slight but in different directions for the first two years.

For all significant treatment effects no interaction between treatment and the weed status of sites was found, nor were differences in treatment effects apparent between sugar beet and fodder beet. Treatment effects were found to differ between environmental zones in two out of 72 analyses. These cases are counts of total butterflies and counts of the dominant species, small white in spring oilseed rape: the direction of the treatment difference was reversed for the Scottish lowlands (environmental zone 4) relative to sites in England.

4. DISCUSSION

The management of GMHT crops had significant effects on the plants and invertebrates of field margins. The main effects were found on the vegetation within the non-cropped tilled margin of fields, which is situated between the crop and the field verge. The overall cover of plant species and the degrees of flowering and seeding of these species were all affected, but the response differed between the three crops studied. Less plant cover, which produced fewer flowers and less seed, was found on tilled margins of GMHT halves of spring oilseed rape fields throughout the season. The tilled margins of GMHT halves of beet also had less flowering and seeding, though this effect was apparent only in July and August. The converse was found on tilled margins of maize fields, with more flowering found on GMHT halves. The effects on tilled margins of the adoption of GMHT management are therefore likely to be markedly different, depending on the crop grown.

Although not part of the cropped area of fields, the tilled margin was cultivated and likely to be managed in a similar way to the adjacent crop. Herbicide may be applied directly. Consequently, effects on weeds in this area of the field were similar to those within the crop, where the density and biomass of weeds, including reproductive individuals, were greater within GMHT maize crops, but less within beet and spring oilseed rape crops (Heard *et al.* 2003*a*). The effects on weeds found within the crop reflect the relative efficacy of GMHT compared with conventional herbicide regimes. In particular, lower weed densities in conventional maize were attributed to the widespread use of herbicides such as atrazine that persist in the soil for long periods (Heard *et al.* 2003*a*). Although the main effects of management of GMHT crops on the vegetation of the adjacent margins were within the often narrow (0.9 m on average) tilled-margin strip, differences were also found in other components of field margins, situated further away from the crop. Notably, the cover of vegetation within the field verge and boundary, and the flowering within the verge, was reduced beside GMHT spring oilseed rape in June. This reduction in flowering did not persist into July and August, however, even though flowering effects within tilled margins were marked at these times of the year. Although greater cover of vegetation was found in field verges beside GMHT maize in June, no resultant effects on flowering and seeding were found. Compared with those in the tilled margin, vegetation effects in the field verge and boundary were therefore fewer in number and smaller in magnitude, and, for flowering and seeding, were not found throughout the season.

Table 4. Index of flowering within tilled margins for plant families important for nectar and pollen for bees and butterflies. (Geometric means for conventional (C) and GMHT treatments are values per 10 m^2 for n sites included in the analysis. Multiplicative treatment ratio, $R = 10^d$, where d is the mean of the differences between GMHT and C treatments on the logarithmic scale; confidence limits for R are back-transformed from those for d. CI, confidence interval.)

			geometric mean			
crop and plant group	period	n	C	GMHT	R (95% CI)	p-value
beet						
Asteraceae	year	64	12.0	6.04	0.52 (0.34–0.79)	0.004**
	June	19	1.41	2.40	1.57 (0.58–4.22)	0.27
	July	53	5.94	1.88	0.35 (0.22–0.57)	< 0.001***
	August	61	6.78	3.43	0.53 (0.34–0.83)	0.005**
Brassicaceae	year	58	4.93	6.13	1.23 (0.79–1.91)	0.34
	June	20	1.35	3.79	2.44 (1.09–5.48)	0.027*
	July	45	3.24	2.75	0.86 (0.49–1.52)	0.60
	August	53	2.22	3.83	1.63 (1.01–2.66)	0.045*
Fabaceae	year	52	1.93	1.91	0.99 (0.63–1.55)	0.97
	June	17	0.56	1.32	1.86 (0.65–5.31)	0.23
	July	39	1.75	0.57	0.44 (0.27–0.71)	0.004**
	August	44	0.80	0.98	1.15 (0.71–1.87)	0.57
Scrophulariaceae	year	56	5.59	5.37	0.96 (0.61–1.51)	0.87
	June	22	1.15	2.00	1.57 (0.73–3.41)	0.27
	July	43	3.81	2.46	0.67 (0.38–1.19)	0.18
	August	46	3.75	2.83	0.78 (0.45–1.32)	0.33
maize						
Asteraceae	year	51	5.72	5.69	1.00 (0.61–1.62)	0.99
	June	11	0.75	2.00	2.15 (0.90–5.10)	0.12
	July	40	2.70	1.83	0.71 (0.38–1.34)	0.34
	August	48	4.09	3.29	0.82 (0.46–1.46)	0.52
Brassicaceae	year	45	1.70	6.59	3.41 (1.90–6.11)	< 0.001***
	June	11	1.07	1.53	1.33 (0.23–7.52)	0.73
	July	27	1.78	2.60	1.39 (0.56–3.46)	0.47
	August	40	0.91	4.49	3.88 (2.02–7.43)	< 0.001***
Fabaceae	year	36	0.86	3.50	3.22 (1.67–6.20)	0.002**
	June	7	0.37	0.49	1.17 (0.40–3.46)	0.82
	July	23	0.36	2.41	3.98 (1.60–9.88)	0.009**
	August	31	0.65	3.01	3.41 (1.82–6.38)	0.002**
Scrophulariaceae	year	41	1.11	5.79	4.24 (2.33–7.73)	< 0.001***
	June	12	0.79	0.74	0.95 (0.39–2.34)	0.91
	July	27	0.85	3.67	3.38 (1.63–6.98)	0.002**
	August	37	0.71	4.49	4.61 (2.52–8.46)	< 0.001***
spring oilseed rape						
Asteraceae	year	67	15.3	7.60	0.51 (0.36–0.72)	< 0.001***
	June	25	1.95	0.51	0.37 (0.19–0.70)	0.005**
	July	61	4.71	2.25	0.51 (0.32–0.83)	0.008**
	August	65	8.31	4.33	0.54 (0.38–0.76)	0.002**
Brassicaceae	year	66	8.36	5.60	0.68 (0.47–0.98)	0.030*
	June	34	2.49	1.13	0.52 (0.30–0.90)	0.015*
	July	56	6.05	2.92	0.51 (0.33–0.80)	0.003**
	August	54	2.72	2.37	0.89 (0.60–1.31)	0.53
Fabaceae	year	51	3.49	2.86	0.84 (0.50–1.40)	0.50
	June	16	1.88	1.01	0.61 (0.23–1.61)	0.32
	July	39	2.38	1.41	0.64 (0.38–1.10)	0.094
	August	48	1.66	1.57	0.96 (0.57–1.61)	0.89
Scrophulariaceae	year	52	8.41	4.35	0.54 (0.35–0.82)	0.007**
	June	28	3.20	1.24	0.45 (0.25–0.80)	0.013*
	July	43	3.91	1.94	0.54 (0.31–0.92)	0.026*
	August	45	3.92	2.14	0.58 (0.37–0.93)	0.026*

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

As well as affecting vegetation in the tilled margin, management of GMHT crops had significant effects on the invertebrates found along field margins. The greatest effects were on butterflies, and were most marked in margins adjacent to spring oilseed rape. The overall density of butterflies was greatest in this crop, and counts were consistently lower on GMHT margins throughout the season. These differences were mirrored within the cropped

Table 5. Scorching of vegetation in field margins.
(Arithmetic means for conventional (C) and GMHT treatments are per cent vegetation scorched per 10 m^2 for n sites included in the analysis. CI, confidence interval.)

crop and margin location	period	n	arithmetic mean count C	arithmetic mean count GMHT	difference between treatments (95% CI)	p-value
beet						
tilled margin	year	66	1.12	5.49	4.37 (2.97–5.77)	$< 0.001^{***}$
	May	34	0.72	1.86	1.14 (−1.28–3.57)	0.34
	June	42	1.38	4.23	2.85 (0.51–5.18)	0.018^{*}
	July	60	1.50	8.17	6.67 (4.54–8.79)	$< 0.001^{***}$
	August	63	0.91	5.06	4.15 (2.06–6.24)	$< 0.001^{***}$
field verge	year	64	1.33	3.83	2.50 (1.74–3.26)	$< 0.001^{***}$
	May	34	0.68	1.94	1.26 (−0.26–2.78)	0.10
	June	40	1.46	3.70	2.24 (1.01–3.47)	$< 0.001^{***}$
	July	58	1.43	5.07	3.64 (2.18–5.11)	$< 0.001^{***}$
	August	60	1.12	3.46	2.34 (1.15–3.52)	$< 0.001^{***}$
boundary	year	61	0.17	0.82	0.65 (0.19–1.11)	0.007^{**}
	May	32	0.05	0.02	−0.04 (−0.15–0.08)	0.54
	June	39	0.42	0.66	0.24 (−0.10–0.58)	0.17
	July	53	0.15	0.96	0.80 (0.11–1.50)	0.025^{*}
	August	56	0.18	0.86	0.67 (0.01–1.34)	0.047^{*}
maize						
tilled margin	year	58	1.24	4.32	3.09 (1.59–4.59)	$< 0.001^{***}$
	June	43	2.18	6.71	4.53 (1.61–7.45)	0.003^{**}
	July	52	1.20	5.14	3.94 (1.56–6.33)	0.002^{**}
	August	51	0.47	0.47	0.00 (−0.50–0.51)	0.99
field verge	year	58	1.63	3.10	1.47 (0.60–2.35)	$< 0.001^{***}$
	June	43	2.74	4.82	2.08 (0.28–3.88)	0.024^{*}
	July	51	1.25	3.75	2.50 (1.18–3.83)	$< 0.001^{***}$
	August	51	0.96	0.90	−0.06 (−0.74–0.62)	0.87
boundary	year	58	0.43	0.56	0.13 (−0.17–0.44)	0.39
	June	42	0.57	1.10	0.53 (0.05–1.00)	0.030^{*}
	July	50	0.34	0.54	0.20 (−0.31–0.71)	0.43
	August	50	0.15	0.18	0.03 (−0.07–0.12)	0.59
spring oilseed rape						
tilled margin	year	64	1.02	3.55	2.54 (1.56–3.52)	$< 0.001^{***}$
	June	52	2.01	8.07	6.06 (3.37–8.75)	$< 0.001^{***}$
	July	54	1.30	2.96	1.66 (−0.11–3.43)	0.065
	August	61	0.22	0.49	0.28 (−0.13–0.68)	0.18
field verge	year	64	1.99	4.02	2.02 (1.01–3.03)	$< 0.001^{***}$
	June	51	3.02	6.89	3.87 (1.49–6.26)	0.002^{**}
	July	54	2.76	4.14	1.38 (−0.22–2.97)	0.09
	August	60	0.60	1.32	0.72 (−0.21–1.65)	0.12
boundary	year	65	1.08	1.43	0.35 (−0.36–1.06)	0.33
	June	49	0.97	0.96	−0.02 (−0.51–0.48)	0.94
	July	53	1.30	1.42	0.13 (−0.54–0.80)	0.71
	August	58	0.37	0.63	0.26 (−0.50–1.01)	0.50

$^{*}\ p < 0.05$; $^{**}\,p < 0.01$; $^{***}\,p < 0.001$.

area of the field (Haughton *et al.* 2003), where butterfly counts were also lower in the GMHT half. The magnitudes of these effects on butterfly density were also remarkably similar, with 22% lower numbers within the crop and 24% less within adjacent margins. Effects on butterfly numbers were also found in margins of beet crops but these differed through the season: fewer butterflies were found on GMHT margins in July, but not earlier in the season. Within the crop, however, butterfly numbers were lower in the GMHT half only in August (Haughton *et al.* 2003). Counts of butterflies in margins adjacent to maize were not different between treatments despite differences being apparent within the field (Haughton *et al.* 2003). Compared with spring oilseed rape and beet, tilled margins of maize had less overall flowering, which differed between treatments only in August.

For mobile insects such as bees and butterflies, it is likely that densities on margins and within the adjacent crop are closely related, but there was also a good match between effects on butterfly numbers on margins and on flowers within tilled margins throughout the season. It

Table 6. Butterfly counts on field margins in relation to treatments in each half-field.
(Year totals are based on four visits for beet sites, and three visits for maize and spring oilseed rape sites. Geometric means for conventional (C) and GMHT treatments are numbers per 300 m of transect for n sites included in the analysis. Multiplicative treatment ratio, $R = 10^d$, where d is the mean of the differences between GMHT and C treatments on the logarithmic scale; confidence limits for R are back-transformed from those for d. CI, confidence interval.)

			geometric mean			
crop and taxa	period	n	C	GMHT	R (95% CI)	p-value
beet						
total butterflies	year	66	11.4	9.09	0.82 (0.66–1.01)	0.064
	May	25	2.14	1.86	0.91 (0.61–1.35)	0.60
	June	22	1.24	1.75	1.23 (0.79–1.89)	0.35
	July	54	5.19	3.51	0.73 (0.54–0.99)	0.042*
	August	58	5.30	4.17	0.82 (0.64–1.06)	0.14
Pieris brassicae	year	37	2.30	2.11	0.94 (0.65–1.37)	0.78
Pieris rapae	year	51	4.06	3.32	0.85 (0.66–1.11)	0.25
Pieris napi	year	24	1.74	1.79	1.02 (0.68–1.52)	0.94
Aglais urticae	year	31	3.57	1.29	0.50 (0.31–0.80)	0.005**
Inachis io	year	16	2.50	1.08	0.59 (0.32–1.11)	0.11
Maniola jurtina	year	34	2.34	2.29	0.99 (0.74–1.31)	0.93
maize						
total butterflies	year	56	11.6	11.3	0.98 (0.79–1.22)	0.88
Pieris brassicae	year	32	1.90	2.79	1.31 (0.94–1.83)	0.12
Pieris rapae	year	44	3.78	3.15	0.87 (0.69–1.09)	0.22
Pieris napi	year	14	2.85	1.94	0.76 (0.46–1.26)	0.22
Aglais urticae	year	27	2.54	1.90	0.82 (0.52–1.30)	0.36
Inachis io	year	18	1.57	1.19	0.85 (0.51–1.42)	0.53
Pyronia tithonus	year	23	2.26	1.71	0.83 (0.47–1.47)	0.53
Maniola jurtina	year	36	2.26	2.68	1.13 (0.80–1.59)	0.45
Aphantopus hyperantus	year	16	1.72	1.96	1.09 (0.60–1.98)	0.81
spring oilseed rape						
total butterflies	year	67	24.5	18.3	0.76 (0.64–0.90)	0.003**
	June	42	2.84	2.08	0.80 (0.58–1.11)	0.17
	July	57	9.37	5.34	0.61 (0.48–0.78)	< 0.001***
	August	64	13.2	10.9	0.84 (0.70–1.01)	0.055
Pieris species	year	67	16.7	13.2	0.81 (0.67–0.96)	0.024*
	June	37	2.68	2.06	0.83 (0.57–1.22)	0.36
	July	51	5.44	2.94	0.61 (0.48–0.78)	0.002**
	August	61	10.4	9.77	0.95 (0.76–1.17)	0.62
non-*Pieris* species	year	61	7.20	4.12	0.63 (0.50–0.79)	< 0.001***
	June	7	1.03	1.03	1.00 (0.39–2.57)	1.00
	July	48	4.96	2.92	0.66 (0.48–0.90)	0.013*
	August	47	3.55	1.75	0.60 (0.48–0.77)	< 0.001***
Pieris brassicae	year	52	4.05	3.59	0.91 (0.66–1.25)	0.55
Pieris rapae	year	65	10.9	8.91	0.83 (0.70–0.99)	0.034*
Pieris napi	year	31	2.61	1.15	0.60 (0.40–0.89)	0.011*
Inachis io	year	16	2.23	0.98	0.61 (0.36–1.04)	0.090
Aglais urticae	year	29	2.65	1.41	0.66 (0.41–1.05)	0.084
Pyronia tithonus	year	13	3.42	1.36	0.53 (0.29–0.99)	0.073
Maniola jurtina	year	31	2.56	1.87	0.81 (0.53–1.22)	0.28
Aphantopus hyperantus	year	23	3.60	2.07	0.67 (0.41–1.10)	0.11

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

therefore seems likely that these mobile nectar-feeding insects were simply responding to availability of forage resource. Flower density has been shown to affect the density of butterflies on field margins (Clausen *et al.* 2001; Dover 1996; Feber *et al.* 1996; Meek *et al.* 2002; Sparks & Parish 1995). These studies highlight the importance of particular plants for nectar, many of which belong to the Asteraceae (e.g. thistles), one of the plant families with reduced flowering in tilled margins of beet and spring oilseed rape GMHT crops. Related work has also shown the importance of nectar resource in arable systems for bees (Backman & Tiainen 2002; Dramstad & Fry 1995; Fussell & Corbet 1992*a*; Saville 1993), but we did not detect comparable effects of GMHT management on this group of species. This could be the result, in part, of low and variable counts, and, in spring oilseed rape, of a buffering effect of the crop, which provides copious nectar and pollen on both treatments when in flower.

In arable ecosystems, weeds are an important source of pollen and nectar for invertebrates. This study has

Table 7. Bees on field margins in relation to treatments in each half-field.
(Year totals are based on four visits for beet sites, and three visits for maize and spring oilseed rape sites. Geometric means for conventional (C) and GMHT treatments are numbers per 300 m of transect for n sites included in the analysis. Multiplicative treatment ratio, $R = 10^d$, where d is the mean of the differences between GMHT and C treatments on the logarithmic scale; confidence limits for R are back-transformed from those for d. CI, confidence interval.)

			geometric mean			
crop and taxa	period	n	C	GMHT	R (95% CI)	p-value
beet						
total bees	year	63	9.12	8.12	0.90 (0.66–1.23)	0.50
	May	19	1.52	1.09	0.83 (0.46–1.51)	0.53
	June	35	2.18	3.22	1.33 (0.86–2.04)	0.17
	July	47	4.04	4.01	1.00 (0.69–1.44)	0.98
	August	44	3.46	2.34	0.75 (0.47–1.18)	0.21
Apis mellifera	year	26	2.36	2.63	1.08 (0.61–1.93)	0.79
	June	13	2.58	0.71	0.48 (0.25–0.91)	0.044*
	July	13	1.28	2.95	1.73 (0.73–4.08)	0.18
bumble-bees	year	63	7.43	6.43	0.88 (0.65–1.20)	0.43
	May	15	1.65	0.93	0.73 (0.36–1.48)	0.34
	June	30	1.49	3.32	1.74 (1.17–2.59)	0.013*
	July	46	3.61	3.32	0.94 (0.64–1.37)	0.70
	August	41	3.36	2.15	0.72 (0.45–1.17)	0.20
long-tongued bees	year	45	3.02	2.75	0.94 (0.63–1.39)	0.71
	June	18	0.83	2.14	1.71 (1.09–2.70)	0.028*
	July	19	2.08	1.64	0.86 (0.46–1.58)	0.59
	August	27	1.82	1.33	0.83 (0.47–1.47)	0.50
maize						
total bees	year	54	7.48	7.60	1.01 (0.75–1.37)	0.92
Apis mellifera	year	27	2.00	3.58	1.53 (0.95–2.47)	0.081
	June	11	1.91	1.63	0.91 (0.44–1.88)	0.80
	July	10	3.14	2.79	0.92 (0.31–2.75)	0.87
	August	15	0.54	3.35	2.82 (1.63–4.90)	< 0.001***
bumble-bees	year	53	6.08	5.48	0.92 (0.68–1.24)	0.55
long-tongued bees	year	35	2.31	1.72	0.82 (0.57–1.20)	0.32
spring oilseed rape						
total bees	year	67	14.1	13.5	0.96 (0.76–1.22)	0.75
Apis mellifera	year	50	3.29	3.61	1.07 (0.75–1.53)	0.68
bumble-bees	year	67	9.69	9.46	0.98 (0.77–1.25)	0.87
long-tongued bees	year	50	2.36	2.36	1.00 (0.75–1.33)	1.00

* $p < 0.05$; *** $p < 0.001$.

Table 8. Gastropods totalled over two sampling occasions, in relation to treatments in each half-field.
(Geometric means for conventional (C) and GMHT treatments are numbers per 24 m^2 for n sites included in the analysis. Multiplicative treatment ratio, $R = 10^d$, where d is the mean of the differences between GMHT and C treatments on the logarithmic scale; confidence limits for R are back-transformed from those for d. CI, confidence interval.)

		geometric mean			
crop and taxa	n	C	GMHT	R (95% CI)	p-value
beet					
total gastropods	64	54.1	57.3	1.06 (0.84–1.34)	0.64
slugs	61	10.0	7.95	0.81 (0.64–1.03)	0.080
snails	61	35.3	37.8	1.07 (0.81–1.41)	0.65
maize					
total gastropods	58	86.1	82.7	0.96 (0.81–1.14)	0.65
slugs	54	10.7	8.93	0.85 (0.68–1.06)	0.15
snails	58	53.0	49.3	0.93 (0.73–1.20)	0.56
spring oilseed rape					
total gastropods	66	86.9	75.7	0.87 (0.70–1.09)	0.24
slugs	58	13.2	10.9	0.84 (0.63–1.12)	0.25
snails	60	61.0	54.4	0.89 (0.68–1.17)	0.41

Table 9. Invertebrates sampled by suction sampling of the field verge, in relation to treatments in each half-field for (*a*) taxonomic groups and (*b*) functional groups.
(Geometric means for conventional (C) and GMHT treatments are numbers per 0.56 m^2 for n sites included in the analysis. Multiplicative treatment ratio, $R = 10^d$, where d is the mean of the differences between GMHT and C treatments on the logarithmic scale; confidence limits for R are back-transformed from those for d. CI, confidence interval.)

			geometric mean			
(*a*) crop and taxa	period	n	C	GMHT	R (95% CI)	p-value
beet						
total Carabidae	year	60	4.34	3.56	0.85 (0.69–1.06)	0.16
total Araneae	year	64	17.9	15.9	0.89 (0.73–1.10)	0.26
total Heteroptera	year	58	10.6	8.71	0.84 (0.63–1.13)	0.24
herbivorous species	year	40	1.84	1.52	0.89 (0.59–1.33)	0.55
	June	12	2.23	0.60	0.50 (0.26–0.95)	0.024*
	August	34	1.46	1.43	0.99 (0.64–1.54)	0.98
total Collembola	year	64	113	125	1.10 (0.81–1.50)	0.51
maize						
total Carabidae	year	51	3.46	3.65	1.04 (0.83–1.32)	0.72
B. lampros	year	22	0.65	2.38	2.05 (1.37–3.07)	0.003**
D. atricapillus	year	9	2.61	1.03	0.56 (0.38–0.83)	0.027*
total Araneae	year	57	24.4	20.3	0.84 (0.71–1.00)	0.046*
Linyphiidae	year	55	8.30	5.64	0.71 (0.58–0.88)	0.003**
total Heteroptera	year	54	12.7	12.1	0.96 (0.77–1.21)	0.73
total Collembola	year	57	152	170	1.12 (0.87–1.43)	0.38
	June	52	64.9	74.6	1.15 (0.85–1.55)	0.38
	August	53	73.9	101	1.37 (1.02–1.84)	0.049*
spring oilseed rape						
total Carabidae	year	58	3.16	2.83	0.92 (0.73–1.16)	0.50
total Araneae	year	65	14.3	13.2	0.93 (0.74–1.16)	0.53
Linyphiidae	year	60	6.36	5.28	0.85 (0.69–1.06)	0.14
	June	41	3.21	1.81	0.67 (0.49–0.91)	0.019**
	August	53	4.19	4.34	1.03 (0.80–1.33)	0.83
total Heteroptera	year	47	7.57	6.65	0.89 (0.71–1.13)	0.35
total Collembola	year	65	105	113	1.07 (0.84–1.37)	0.55
Sminthuridae	year	54	8.31	12.8	1.48 (0.91–2.43)	0.12
	June	45	8.80	11.6	1.29 (0.68–2.44)	0.43
	August	36	2.23	4.46	1.69 (1.08–2.63)	0.027*

			geometric mean			
(*b*) species group	period	n	C	GMHT	R (95% CI)	p-value
beet						
herbivores	year	64	51.8	41.5	0.81 (0.63–1.03)	0.077
	June	56	17.4	18.8	1.07 (0.79–1.46)	0.66
	August	62	30.4	21.7	0.72 (0.55–0.96)	0.023*
predators	year	64	27.9	24.9	0.90 (0.76–1.06)	0.20
parasitoids	year	64	38.2	30.4	0.80 (0.64–1.01)	0.060
	June	56	10.1	11.0	1.09 (0.84–1.41)	0.55
	August	62	27.0	19.1	0.72 (0.55–0.94)	0.017*
bird food	year	64	58.3	51.3	0.88 (0.71–1.09)	0.25
maize						
herbivores	year	57	63.0	68.5	1.09 (0.88–1.34)	0.43
predators	year	57	33.9	31.9	0.94 (0.81–1.09)	0.42
parasitoids	year	57	41.4	41.5	1.00 (0.84–1.20)	0.99
bird food	year	57	76.3	83.4	1.09 (0.91–1.30)	0.34
spring oilseed rape						
herbivores	year	65	37.4	41.5	1.11 (0.92–1.33)	0.27
predators	year	65	20.8	19.5	0.94 (0.79–1.13)	0.54
parasitoids	year	65	41.3	41.7	1.01 (0.87–1.17)	0.91
bird food	year	65	48.8	49.1	1.01 (0.87–1.16)	0.89

* $p < 0.05$; ** $p < 0.01$.

suggested that weeds within the tilled non-cropped component of field margins, and within the crop edge, may be important for the following reasons. Field-margin vegetation adjacent to the cropped area of fields, at least within the first 20 cm (Kleijn 1996), is likely to capture fertilizers applied to the crop. As well as having increased productivity, vegetation in this part of the boundary has a higher percentage of annual species (Kleijn & Verbeek 2000). Plants growing in such a habitat, in the absence of crop plants, are also more likely to flower and produce seed because there is less competition. Equally, an important trait of plants that predominate in such situations is the production of a large number of flowers. Although flowering of any particular species may occur only over a short period, the temporally separate flowering periods of a diverse weed community can provide a regular supply of pollen and nectar, particularly for generalist feeders. In addition, plants in the tilled margin may be particularly important to larger flower-visiting insects, as they are likely to be more apparent than similar resources within the crop. Butterflies may also benefit from the proximity of this nectar supply to boundaries, which provide shelter, larval foodplants and to a lesser extent insulation for these species (Dover & Sparks 2000).

It is likely that the effects observed on butterflies were mostly, but not solely, caused by differences in the nectar resources provided by arable plants. The availability of larval food resources in margins may be important for some species (Feber *et al.* 1996) but the consistency of the effects found for the separate butterfly species, which have different larval foodplant requirements, suggests a mechanism common to all species.

Effects on butterfly numbers could also be caused by differences in the toxic effects of herbicides, or insecticides, used between the two halves of the field. Applications of insecticides were almost always the same for the two halves of the field (Champion *et al.* 2003) and there are few examples of direct toxic effects of herbicides on invertebrates (Norris & Kogan 2000). The most important effects of herbicides on invertebrates are likely to be indirect, through the effects on the host plants, by modification of food resource and habitat (Potts 1986). The GMHT and conventional crops may also differ in other aspects important for butterflies. Whether the two varieties differ in attractiveness cannot be assessed from these FSEs, but previous work suggests this is unlikely, at least for bees (Osborne *et al.* 2001; Picard-Nizou *et al.* 1995). Differences in flowering duration between conventional and GMHT crops are also unlikely to be important. Beet did not provide nectar or pollen, because it was not allowed to flower (Champion *et al.* 2003), and the effects observed in spring oilseed rape were found in July and August after the crop had finished flowering. Further, no differences were found in the overall frequency of crop flowering between GMHT and conventional spring oilseed rape (Hawes *et al.* 2003).

From the results of this experiment, it is not possible to draw direct conclusions about the impact of GMHT management on the long-term dynamics of butterfly populations. We have no measurements of densities at sites in subsequent years and all the common species are highly mobile. The effects on butterfly numbers relating to nectar resources in tilled margins demonstrate a foraging choice. If sufficient forage resource is available elsewhere in the landscape, then populations of this mobile species group will be buffered against the effects of changes in herbicide management, but not if forage reductions occur over large contiguous areas. Of the butterfly species commonly found in arable ecosystems, those with lower dispersal ability (e.g. hedge brown, *Pyronia tithonus*) are likely to be most vulnerable to changes in the availability of nectar plants. For these species in particular, but also for butterfly populations in general, landscape structure is likely to be more important than the farming system (Sherratt & Jepson 1993; Weibull *et al.* 2000). Loss and degradation of field margins associated with agricultural intensification has been suggested as a cause of the decline in butterflies in the UK (Asher *et al.* 2001) and other European countries (Maes & van Dyck 2001; van Swaay 1990), but the relative importance of field margins versus other suitable habitats such as road verges and waste places has not been quantified. Whether resources for adult (nectar) and/or larval (foodplants) butterflies are limited in agro-ecosystems is not known, and scaling up the results of this experiment poses similar problems to those identified for predicting the effects of GMHT cropping on skylark populations (Firbank & Forcella 2000; Watkinson *et al.* 2000).

This experiment has demonstrated the indirect effects of herbicide management on butterflies; similar effects may be expected for other flower- and nectar-feeding groups such as solitary bees, moths, hoverflies and other flies, as well as less frequent nectar feeders such as beetles and wasps (Vespidae species and larger parasitic groups such as the Ichneumonidae). Effects on such a range of species groups could have implications for the pollination of arable plants (Allen-Wardell *et al.* 1998). The effects on seeding may also have knock-on effects on arable food webs. Differences in the frequency of species that set seed in tilled margins mirrored effects on seed rain found within the crop (Heard *et al.* 2003*a*) whereby seeding was lower in GMHT beet and spring oilseed rape but greater in GMHT maize. The longer-term implications of such changes depend upon rotational cropping patterns, yet may be important to birds of conservation concern whose densities are related to the availability of dietary seed (Moorcroft *et al.* 2002; Robinson & Sutherland 2002).

The amount of herbicide drift was not measured in this experiment, but the level of scorched vegetation was low in field margins adjacent to both GMHT and conventional half-fields. Although drift of agrochemicals is dependent on several factors, levels reported under normal conditions range from 1 to 15% of the amount applied to the crop at 1 m from the last nozzle (Marrs *et al.* 1989). Differences in the amount of scorched vegetation were found particularly within tilled margins, being greater in the GMHT treatments for all crops. The management of the GMHT crops allowed the herbicides to be applied later in the development of tolerant crops than in conventional non-tolerant varieties (Champion *et al.* 2003). The spray boom was therefore higher, and the potential for spray drift likely to be greater, when herbicide was applied to the GMHT half-fields. At this later stage of the season, more plants will also be actively growing (e.g. fewer are still dormant) and therefore susceptible to drift, but the structure of the vegetation will also affect the deposition of spray droplets: drift may penetrate less distance into field margins when the sward is taller (Marrs *et al.* 1991).

The effects of herbicide-spray drift on plants and animals of the field margins have proved hard to measure and predict (Marrs & Frost 1997). Scorching of vegetation was greater on GMHT field margins, notably tilled margins, the component of field margins where 15 out of the 22 effects on cover, flowering and seeding of vegetation were found. Less evidence for marked treatment effects were found in field-verge or boundary vegetation. Plant cover was lower in these components of field margins in GMHT spring oilseed rape when sampled in June, however, the time of the year when spray-damage effects were greatest. Flowering was also lower in GMHT spring oilseed rape verges at this time, but not later in the season when spray-damage effects were reduced. Seeding of vegetation was also not affected, suggesting some recovery by the vegetation. Experimental studies have suggested that drift of herbicides has less severe effects on field-margin vegetation than does drift of fertilizer applications (Kleijn & Snoeijing 1997).

Slugs, snails and other invertebrates sampled directly from the field verge showed few differences. Where effects were detected for these taxa, abundance was affected both negatively and positively in GMHT treatments. Abundance was lower under GMHT crop management mainly in taxa that use vegetation directly as foodplants, such as the herbivorous true bugs (Heteroptera) (Southwood & Leston 1959) and other arthropods, and in those that use plants as structures for web-spinning (e.g. many sheet web spiders (Linyphiidae); Alderweireldt 1994) or climbing in search of prey (e.g. *D. atricapillus*; Forsythe 2000). The lower densities of the functional groups herbivores and parasitoids in August samples from GMHT beet reflect differences found for these groups within the field, albeit at lower magnitudes (Hawes *et al.* 2003). Biomass of weeds in the crop was also lower at this time of the season in GMHT beet (Heard *et al.* 2003*a*), but differences were not detected in the cover and flowering of vegetation of the verge for this crop. There may be movement of individuals between the crop and the field verge for these groups. The lower counts of web sheet spiders in GMHT spring oilseed rape verges may relate directly to vegetation differences found in the verge, however. Many of these spiders use plants in web-building, and reductions in vegetation height have been shown to lead to a lower abundance of one such species, *Lepthyphantes tenuis* (Haughton *et al.* 2001). Less vegetation cover may have provided fewer potential web-building sites for these spiders.

The lack of a difference in the response between fodder beet and sugar beet suggested that the management of these crops is sufficiently similar that they may be treated as one crop for analysis. The consistency of the treatment effects at sites within a range of environmental regions and with differing degrees of overall weed density implied that they could be scaled up to a wider population of sites across the UK. However, the effects on field margins differed between the three crops studied, and predicting the potential effects of commercial growing of GMHT spring-sown crops on farmland biodiversity requires an approach that considers the entire farmed landscape.

In conclusion, this experiment has shown that the effects of GMHT management on the plants of field margins are most marked in the non-cropped tilled strip between the crop and field verge, and carry over to a lesser extent to the verge and field boundary. Vegetation in this component of field margins receives most, if not all, of the herbicide spray applied to weeds in the crop, and pronounced treatment differences in flowering had knock-on effects on butterfly abundance. The effects differed between the three crops studied, however, with less flowering and fewer butterflies on margins of GMHT spring oilseed rape and beet, but more flowering on maize GMHT margins yet no butterfly differences for this crop. Although scorching of vegetation through spray drift was greater on GMHT field verges, the overall percentage of vegetation affected was very low. No other marked effects were found on plants and invertebrates living in the field verge or boundary. Out of the invertebrate groups sampled, butterflies have been shown to be particularly sensitive to differences in vegetation. This highlights their importance as a key indicator species in future studies of agro-ecosystems.

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GLOSSARY

BMS: Butterfly Monitoring Scheme
FSE: Farm Scale Evaluation
GMHT: genetically modified herbicide tolerant